

# Design of a More Accurate, Higher Fidelity, Dual-Source Air Mass Zero Solar Simulator

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13. ABSTRACT (Maximum 200 words)  A dual-source solar simulator has been designed that provides a more accurate, higher fidelity spectral match to the Air Mass Zero (AM0) solar spectrum in comparison to presently available conventional and state-of-the-art solar simulators. The dual-source solar simulator design combines the ultraviolet (UV) light from a xenon arc lamp and the visible and infrared (IR) light from a tungsten lamp using standard wide-band hot and cold mirrors. However, additional filtering is required to match the dual source and AM0 spectra. It was determined that the required transmission function cannot be met with a single filter, so separate filtering of the individual sources was necessary. A standard color glass filter has been chosen to both change the shape of the xenon UV spectrum and reduce the magnitude of the high-intensity spikes in the visible and IR wavelengths. A custom thin-film filter was designed to meet the required transmission function of the visible and IR portions of the tungsten light. The combined, filtered spectra provides a more accurate spectral distribution and integral energy match to the AM0 spectrum over the entire wavelength range while completely removing the common high-intensity xenon arc lamp spikes. The design is presented by comparing conventional solar simulators, identifying the limitations posed by the presence of spikes in the xenon arc lamp spectrum, analyzing each of the separate components of the design and their system impacts, and concluding with additional options or variations that may improve the accuracy range of the dual-source solar simulator.			
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## Introduction

Present day space applications of solar cells require that accurately calibrated, precision equipment be used for tests and measurements. The most critical single unit is the light source. Because advanced solar cells can be extremely sensitive to the spectral content of the incident light, it is necessary to test cells under a light with spectral characteristics similar to those of the sun in space, the Air Mass Zero (AM0) spectrum. This is particularly true for multijunction solar cells. Most conventional solar simulators are based on xenon arc lamps, which are known to have several high-intensity spikes. The presence of high-intensity spikes in the simulator spectrum can cause significant variations between test measurements and actual performance in space. There has been a great deal of effort aimed at filtering the xenon arc lamp to better match the AM0 spectrum and remove the high-intensity spikes, but their complete elimination has been unsuccessful. Dual-source solar simulators have been developed to provide a better match to the AM0 spectrum, but complete removal of the xenon arc lamp high-intensity spikes and a spectral match over the entire wavelength range has yet to be obtained.

This report outlines the design of a more accurate, higher fidelity, dual-source solar simulator as compared to available designs. The accuracy of a solar simulator is determined by comparing both the general shape of the spectral distribution and the integral energy of the simulator to that of the AM0 spectrum. The fidelity of a solar simulator refers to the spectral characteristics over a small wavelength range. A low-fidelity solar simulator may have many high-intensity spikes in its spectral output, but the integral energy and general shape of the spectrum may match the AM0 spectrum. A high-fidelity solar simulator would not have such spikes and would match the AM0 spectrum at all wavelengths.

To begin the design of a dual-source solar simulator that better approximates the AM0 solar spectrum, it is important to first compare conventional solar simulators to the AM0 spectrum. Figure 1 shows the AM0 solar spectrum.<sup>1</sup> Integration of the spectrum over the complete wavelength range (0–1000.0  $\mu\text{m}$ ) yields a solar constant of 135.3  $\text{mW/cm}^2$ . Integration of AM0 over the plotted wavelength range (250–2400 nm) yields 129.27  $\text{mW/cm}^2$  (95.5% of the total integral energy). Also shown in Figure 1 is the calculated irradiation spectrum for a 5800K blackbody with equal integral energy over the 250–2400 nm wavelength range. Evident from the graph is that the sun's spectrum at 1 AU is almost completely modeled by a 5800K blackbody. Shown for comparison is a 3200K blackbody irradiation spectrum (the hottest spectrum of a tungsten source) with equal integral energy over the 250–2400 nm wavelength range. As the temperature of a blackbody decreases, its peak energy decreases in intensity and shifts towards longer wavelengths. Thus, the cooler blackbody spectrum has a greater portion of energy in the infrared (IR). This spectral mismatch is well known since early solar simulators used only tungsten sources. The variations between the different blackbody spectra are also very important when considering the use of a tungsten source to match the IR portion of AM0.

At present, most testing of solar cells is done under xenon arc lamps. Xenon arcs have a nearly constant intensity throughout the visible portion of the spectrum. However, the high-pressure xenon arc lamps have several high-intensity spikes of energy that can greatly affect solar cell

measurements. Despite the great deal of effort that has been directed toward reducing the intensity of the xenon spikes through optical filtering, their elimination has not been successful. Figure 2 shows the spectrum of a typical Spectrolab X-25 (measured in 1989). The X-25 has many different filters aimed at both reducing the high-intensity spikes and providing a uniform, large area spot size. While the X-25 has several high-intensity spikes, the general shape of the curve matches that of AM0. The X-25 has become the industry state-of-the-art and is being widely used throughout the space solar cell community.

## Dual-Source Solar Simulators

The concept of a dual-source solar simulator is not a new one. A dual-source solar simulator using a xenon arc lamp to match the ultraviolet (UV) portion of the AM0 spectrum and a tungsten lamp to match the IR portion was designed in the early 1960's by Hoffman Electronics.<sup>2,3</sup> Three such solar simulators were built, and two are still in operation at the Applied Solar Energy Corporation (formerly owned by the Hoffman Electronics Corp.). The Hoffman simulators use absorbing color-glass filters to isolate the two lamp spectra. The light from the tungsten source is filtered through a red lens that only allows visible and IR light to pass through. The xenon source is filtered by a blue lens that only passes the UV and visible portions of the light. Figure 3 shows the spectral measurements of the Hoffman #1 simulator measured on 22 February 1994. The measurements are very similar to those previously published and attest to the stability of the design.<sup>2,3,4</sup> The design of the Hoffman simulator also allows for easy measurement of the separate blue and red portions of the spectrum by simply blocking the respective lens with an opaque cover. Figure 3 shows the separately measured red and blue spectra. It is evident that the excess energy in the visible portion of the simulator spectrum is caused by the summation of the two light sources. The cut-on of the tungsten source and the cut-off of the xenon source are not ideal. Also, the filtering of the xenon light is not complete, and several of the spikes are apparent in the measured spectrum. The far IR is not shown in the measured spectrum due to the limitations of the silicon photodetector, but other measurements have shown that the dual-source solar simulator has too much energy beyond 1300 nm.<sup>3</sup> This is an expected function of the tungsten source (3200K blackbody) and the red color glass filter. Therefore, very low band-gap materials (i.e., an active Ge junction in a GaAs/Ge solar cell or a GaInP<sub>2</sub>/GaAs/Ge triple-junction cell) would produce more measured current than they would in space.

The Hoffman solar simulator is not the only dual source in existence. Solarex Corporation has designed and built a dual-source solar simulator to better match the AM1.5 (terrestrial) spectrum.<sup>5</sup> Their design uses a xenon arc lamp with a cold mirror that reflects the UV or "cold" portion of the spectrum and an incandescent source with a hot mirror that reflects the IR or "hot" portion of the spectrum to piece wise match the AM1.5 spectrum. However, the intensity of the xenon source is not completely filtered beyond the cut-on wavelength of about 700 nm due to a slight reflectivity in the infrared. The high-intensity spikes transmit through the mirror and are apparent in the combined spectrum of Figure 4. While there are no high-intensity spikes remaining in the combined spectrum, the smaller spikes would still be a problem for accurate solar cell performance measurements. Such a design would not be a significant improvement over the X-25 or Hoffman solar simulators.

## Advanced Dual-Source Solar Simulator Design

To design an advanced dual-source solar simulator that is more accurate and has fewer high-intensity spikes than that already available, alternate spectral filtering is required. The design of the dual-source solar simulator begins with a high-intensity xenon arc lamp and a high-intensity tungsten lamp. In order to splice the two lamp spectra together for an AM0 representation, the spectra must be filtered to reflect and transmit the appropriate portions. A standard wide-band hot mirror is used to reflect the visible and near-IR portion of the xenon arc lamp, and a standard wide-band cold mirror is used to reflect the UV portion of the tungsten lamp. Figure 5 shows the combined dual-source spectrum without using any additional filtering. The spectrum has too much energy in the visible and IR portions and does not follow the general shape of the AM0 spectrum.

To improve the dual-source solar simulator spectral match to AM0, additional spectral filtering is desired. It was determined that standard color glass filters (transmission functions similar to hot mirrors in that they only transmit in the UV and visible portions of the spectrum) may be used because the fairly linear fall-off in transmission in the near IR and the relatively constant transmission in the far IR allow for better spectral matching. In particular, using a Schott KG3 color-glass filter reduces the intensity of the xenon arc lamp in the visible portion of the spectrum and better matches the slope of the AM0 spectrum. In addition, the transmission of the KG3 color-glass filter is less than 0.01 beyond 1000 nm, which almost completely eliminates any spikes in the xenon arc lamp IR spectrum. It was also determined that the Schott KG4 color-glass filter best fit the required transmission function required of the IR portion of the tungsten lamp spectrum. Again, the use of the color-glass filters in addition to the filtering mirrors allow for better spectral matching as a function of wavelength. Figure 6 shows the combined dual-source solar simulator spectrum. While there are two very small spikes remaining in the visible portion of the spectrum, the simulator spectrum is very similar to the AM0 spectrum over the 400–1100 nm range. However, examining Figure 6 over the complete dual-source solar simulator spectrum (400–2400 nm) shows the difficulty in matching the far-IR wavelengths. Because the transmission of the KG4 color-glass filter increases in the IR, the dual-source solar simulator has too much energy beyond 1100 nm. The spectrum of Figure 6 shows only a moderate improvement over the Hoffman dual-source simulator (a better match to the AM0 spectrum in the UV and visible wavelengths and fewer high-intensity spikes in the visible and IR wavelengths).

At this point, there are several items worth mentioning. First and foremost, the design concept has been restricted to using only standard, stock commercial parts. The xenon and tungsten lamps, the hot and cold mirrors, and the color-glass filters are all standard, off-the-shelf products. There are both limitations and benefits to this restriction. The cost reduction and reproducibility of standard products is a desired benefit. However, the spectral transmission functions of the individual components are not ideal. In particular, the commercial hot mirror has nearly zero transmission below 400 nm. Most solar cells are sensitive to light in this wavelength region. However, solar cells used for space are part of a cell/adhesive/coverglass assembly that incorporates additional antireflection coatings. These coatings reflect all incident energy below 350 nm to prevent the adhesive from darkening. While the low intensity in the 350–400 nm range is still present, the

amount of energy in the AM0 spectrum in this wavelength range is small. In addition, a custom hot mirror may be designed to provide transmission down to 350 nm without greatly affecting the designed simulator's performance.

The major limitation in the dual-source solar simulator design of Figure 6 is the additional energy in the IR. With the anticipation of active Ge in GaAs/Ge or GaInP<sub>2</sub>/GaAs/Ge multijunction solar cells, a solar simulator must be accurate out to at least 1880 nm. Therefore, a new custom filter design is required. A dielectric/metal thin-film filter may be designed to provide the required transmission function. The filter consists of multiple thin films of metal and dielectric material deposited on a SiO<sub>2</sub> substrate. The transmission function was theoretically calculated using the commercial Film\*Star lens design program, and such a custom filter can be commercially purchased without greatly increasing the system cost. Using this filter instead of the KG4 color-glass filter to reduce the far-IR portion of the tungsten lamp produces a dual-source solar simulator with the spectral characteristics of Figure 7. Figure 7 shows the complete filtering of the high-intensity spikes from the xenon arc lamp and the complete matching of the AM0 spectrum over the 400–2400 nm range.

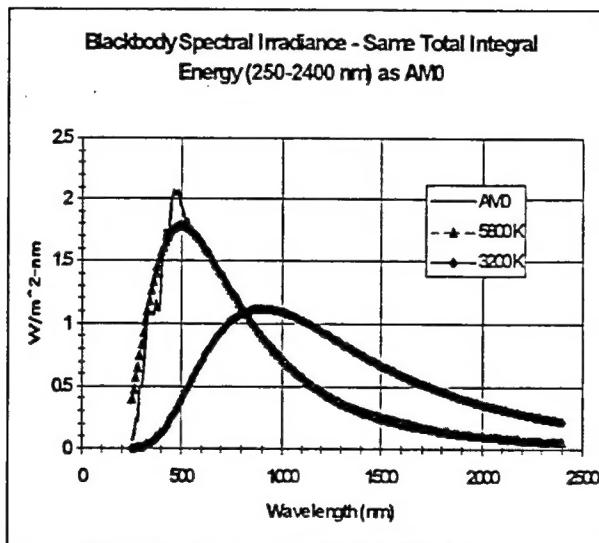


Figure 1. AM0, 5800 K and 3200 K Spectral Irradiance Curves.<sup>1</sup>

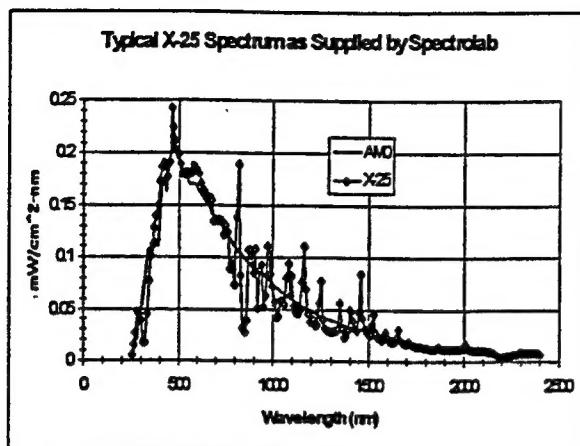


Figure 2. Typical X-25 Solar Simulator As Supplied by Spectrolab.

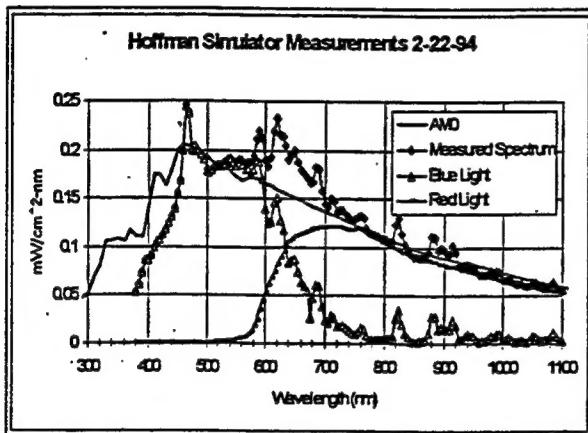


Figure 3. Measured ASEC Hoffman Dual Source Solar Simulator.

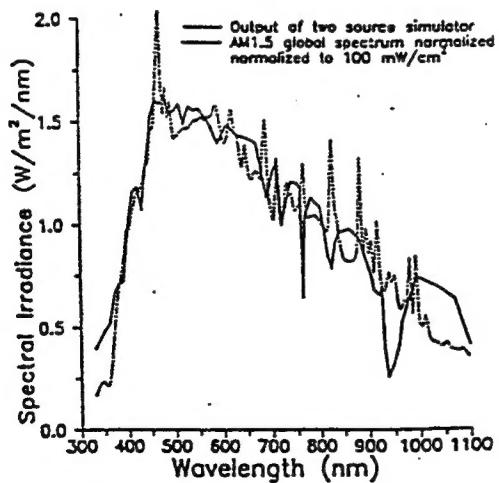


Figure 4. Solarex Dual Source AM1.5 Solar Simulator Spectrum.<sup>5</sup>

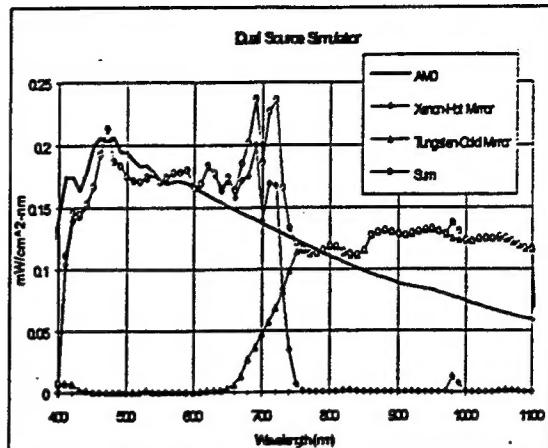


Figure 5. Dual Source Solar Simulator Spectrum Without Additional Filtering.

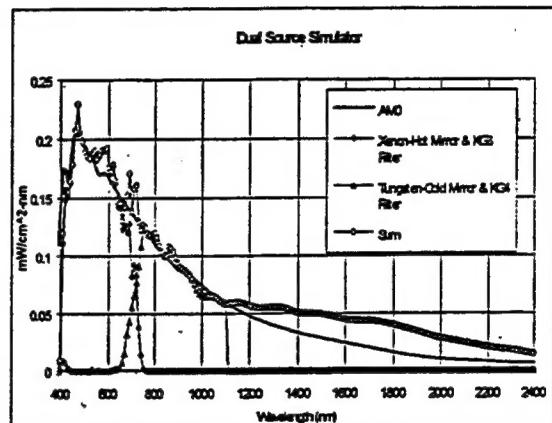


Figure 6. Dual Source Solar Simulator Spectrum Showing IR Rich Spectrum.

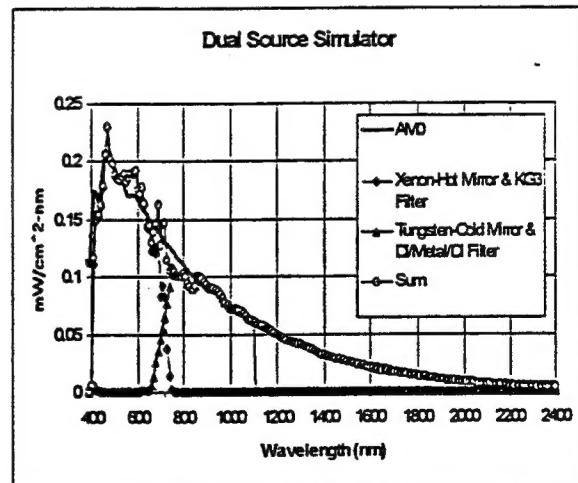


Figure 7. Completely Designed Dual Source Solar Simulator Spectrum.

## **Summary**

In summary, a more accurate, higher fidelity, dual-source solar simulator has been designed that eliminates the high-intensity spikes associated with xenon arc lamps and matches the spectral energy content of AM0 by the combination of wavelength-selective mirrors and optical filters. The design primarily uses standard, off-the-shelf products to reduce both the cost and complexity of the system. However, to accurately match the entire AM0 spectrum, a new dielectric/metal thin-film filter has been specifically designed for this system. This filter is a unique contribution to the system and provides spectral matching to the AM0 spectrum in both the near- and far-infrared regions

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